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Magnitude of Forces Which May be Applied by the Prone Pilot to Aircraft Control Devices. I. Three-Dimensional Hand Control — 52794

Grether, Walter F. — (None)

University of California, Berkeley — (None)

Engineering Division, Air Material Command — MCREXD-694-4J

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A study was made of the forces which pilots could be expected to apply to aircraft controls operated from the prone position. Three dimensions of hand movement suitable for operation of elevator, rudder, and aileron controls were tested on subjects in each of 9 prone positions and in the seated position. From the standpoint of forces which can be applied to hand operated controls, the prone position compares favorably with the seated position. The prone is superior to the seated position for application of pull forces on elevator controls, but is inferior to the seated position for the rotation movement normally used for aileron control. The push right-push left movement dimension, suitable for operation of the rudder controls, is unfavorable for application of high control forces in the prone position.

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Flight Psycholoyg (2)

ATI No. 52794

MEMORANDUM REPORT

U. S. AIR FORCE

AIR MATERIEL COMMAND

WRIGHT-PATTERSON AIR FORCE BASE

DAYTON, OHIO

MCREXD-694-4J

4 March 1949

MAGNITUDE OF FORCES WHICH MAY BE APPLIED BY THE PRONE PILOT TO AIRCRAFT CONTROL DEVICES. I. THREE-DIMENSIONAL HAND CONTROLS, BY C. W. BROWN, E. E. GHISELLI, R. F. JARRETT, E. W. MINIUM AND ROBERT M. U'REN, UNIVERSITY OF CALIFORNIA

Prepared By
University of California

For
Aero Medical Laboratory
Engineering Division

Hq AMC Form No. [illegible]
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U. S. AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE
ENGINEERING DIVISION

No. of Pages - 68
MCREXD9/WFG/maf

MEMORANDUM REPORT ON

4 March 1949

SUBJECT: Magnitude of Forces Which May Be Applied by the Prone Pilot to Aircraft Control Devices. I. Three-Dimensional Hand Controls, By C. W. Brown, E. E. Ghiselli, R. F. Jarrett, E. W. Minium and Robert L. U'Ren, University of California.

SECTION: Aero Medical Laboratory

SERIAL NUMBER: MCREXD-694-4J   Expenditure Order No. 694-17

A. PURPOSE:

1. A report is submitted which has been prepared by Dr. C. W. Brown and co-workers of the University of California under the title of "Magnitude of Forces Which May Be Applied by the Prone Pilot to Aircraft Control Devices". The purpose of the reported study was a determination of the forces which pilots could be expected to apply to aircraft controls operated from the prone position. This study covered three dimensions of hand movement suitable for operation of elevator, rudder, and aileron controls from the prone position. For purposes of comparison, measurements were also made of the forces which could be applied to the identical hand grips from the seated position.

B. FACTUAL DATA:

2. Presented as Appendix I is the third report received from the University of California of completed research on the design of prone position aircraft controls being carried out under Air Materiel Command Contract No. W33-038 ac-15098. Previous reports received under this contract have been published as Memorandum Reports Nos. TSEAA-694-4H and MCREXD-694-4I. Additional studies have been completed of forces which can be applied in several other possible control dimensions. These studies will be described in future reports.

3. Three dimensions of control movement were studied in this experiment, as illustrated in Exhibit A and Figures 1 and 2 of Appendix I. These can be described as "push-pull", "push right-push left", and "rotation" about the longitudinal axis. For flying an aircraft from the prone position these movements would be suitable

for operation respectively of elevators, rudders, and ailerons. Former military pilots who were students at the University of California served as subjects. By use of a hydraulic system which permitted only slight movement of the control, measurements were made of the forces in pounds which could be applied at the hand grips in the various dimensions using both hands. Measurements included both maximum forces and what the pilots judged to be reasonable forces, for nine positions of the prone bed with respect to the control grips. Comparable measurements were made for one seated position while operating the same grips in the same control dimensions.

4. For a detailed description of the experiment and the results the reader is referred to Appendix I. The most significant data, namely, the maximum forces to be expected from the strongest, average, and weakest pilots is shown in Exhibit A, along with an illustration of the control dimensions. Other significant findings may be summarized as follows:

a. For performance of the same movements on hand grips the prone position compared favorably with the seated position (See Table 5, Appendix I). While in the seated position more force could be applied in the "push" direction, the prone-position permitted the pilots to apply more force in the "pull" direction. For "rotation" about the longitudinal axis (suitable for aileron control) the seated was somewhat superior to the prone position. For the "push right-push left" movement the prone position was slightly superior to the seated.

b. There was no clearly optimum position of the prone bed with respect to the controls (See Table 2, Appendix I). A position which was most favorable for one control dimension tended to handicap other control dimensions. For all movements combined the front middle bed position gave the highest average control force.

c. Of the three movements studied the "push right-push left" dimension gave the lowest and the "push-pull" dimension the highest control forces (See Exhibit A, and Appendix I).

C. CONCLUSIONS:

5. The following conclusions can be drawn from this study:

a. From the standpoint of forces which can be applied to hand operated controls the prone position compares favorably with the seated position for aircraft pilots.

b. The "push right-push left" movement dimension, suitable for operation of rudder controls, is unfavorable for application of high control forces. Its use in the prone position, as opposed to foot operated pedals in the seated position, would increase the need for boost in the rudder control system.

c. The prone position is inferior to the seated position for the "rotation" movement normally used for aileron control. Use of the prone position would, therefore, increase the need for boost in the aileron control system.

d. The prone is superior to the seated position for application of "pull" forces on elevator controls.

e. Although there appears to be no position of the prone bed with reference to the control grips which is optimum for application of force in all movement dimensions the front middle height position is probably the best compromise. For this bed position the grips in the neutral position are 5 inches below and 9 inches forward of the pilot's shoulders.

D. RECOMMENDATIONS:

6. It is recommended that the findings of this investigation be applied by the Design Branch of the Aircraft Laboratory and the Biophysics Branch of the Aero Medical Laboratory in future research installations of prone position controls in aircraft.

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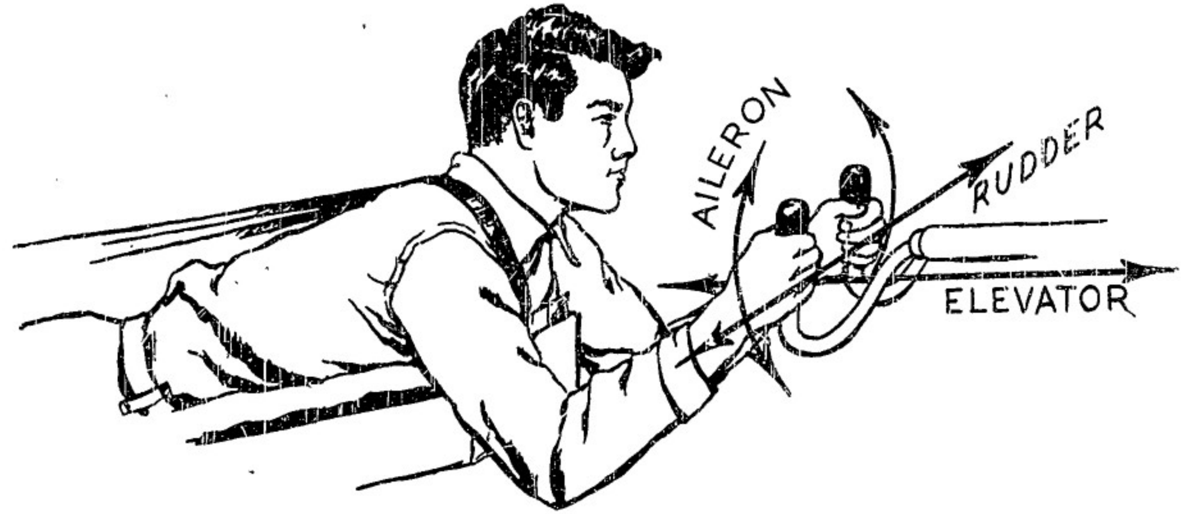

Control dimension	Maximum control forces to be expected from pilots at point of grip (combined force of two hands)		
	Strongest 1% of pilots	Average pilot	Weakest 1% of pilots
Elevator	439	262	85
Rudder	201	123	45
Aileron	209	139	69

Exhibit A. Illustration of three prone position control dimensions and the maximum forces which the strongest, average, and weakest pilots can be expected to apply to such controls.

APPENDIX I

REPORT NO. 3

Aviation Psychology Project
Department of Psychology
University of California
Berkeley, California

MAGNITUDE OF FORCES WHICH MAY BE APPLIED BY THE PRONE PILOT TO AIRCRAFT CONTROL DEVICES. 1. Three-Dimensional Hand Controls.

Prepared for

Aero Medical Laboratory
Engineering Division
Air Materiel Command
Wright-Patterson Air Force Base
Dayton, Ohio

by
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January, 1949

Contract # W 33-038-ac-15098

MAGNITUDE OF FORCES WHICH MAY BE APPLIED BY THE PRONE PILOT TO AIRCRAFT CONTROL DEVICES. 1. Three-Dimensional Hand Controls.

Introduction

Once the advisability of placing the pilot of some particular aircraft in the prone position has been conceded, the problem immediately arises as to the nature of the controls with which he should be provided. In view of the many ways in which the experience of the pilot of an airborne craft differs from that of the operator of any grounded substitute for such a craft, it appears clear that the only valid test of the relative efficiencies of several apparently feasible types of control must lie in the comparison of the speed of learning and ultimate performance of groups of men initially learning to fly in the prone position with the several possible control devices. Some of the questions raised by the problem, however, may be answered by earth-bound research.

Logical analysis reveals many movements and combinations of movements which might be employed in the design of aircraft controls. Some of these possible combinations are suitable for operation by the seated pilot, and it is reasonable to believe that in more than thirty years of experience with the control of aircraft from the seated position the most effective controls would have survived. The writers, however, are not aware of any psychological study aimed at the discovery of the ideal system of control from the seated position.

The long and successful use of the stick-and-rudder or wheel-and-rudder system for the control of conventional planes is a powerful suggestive influence upon the design of controls for craft which must be flown from the prone position. The psychologist's experience with many similar problems, however, would indicate that the mere modification of such controls so they could be used by the prone pilot would not necessarily constitute the ideal solution to this problem. Indeed, subjective experience suggests immediately that rudder-control with such a device would be most fatiguing and perhaps inefficient.

The necessity of changing the position of the pilot from the seated to the prone position thus provides an opportunity to consider control mechanisms quite different from the conventional ones, and the investigation to be reported in this paper has concerned itself with a three-dimensional hand control which, on a priori grounds, seemed most likely to be optimal for the prone control of aircraft. We have arrived at our decision to investigate this particular system of hand controls on the basis of the following considerations.

The possibility of injury to one side of the body, as well as the necessity for the pilot to manipulate other objects than the controls, demands that any system of controls should be capable of operation by one hand.* The often-reported dependence of pilots upon the "feel" of the controls further demands that they be of such nature as to require work on the part of the pilot.** The degrees of freedom available for consideration, then, are the degrees of freedom of a point (within the grip of one hand), the manipulation of which requires that an appreciable amount of work be done.***

The weakness of wrist movements implies that of the six degrees of freedom of a point in space (three of translation and three of rotation) which must be manipulated by one hand, only those associated with translation can be employed for doing work. Thus only the three degrees of freedom of translation are available.

Since it may often be possible for the pilot to use both hands in controlling the plane, two controlling points must be provided, and these two points may be linked together in several ways, all of which permit each point motion of translation in the same three dimensions. The linkage between these

---

* The Tison control constructed during the war for use with an experimental model of a prone-flown plane suffers the serious disadvantage that it cannot be operated in all three dimensions of control by a single hand.

** If no work were done, the only information available to the pilot would be by way of the position of the control grips, and this is almost useless in a rate-controlled situation such as aircraft control. In this connection it is of interest to note the findings of Helson (1) that in general and within rather broad limits, tracking operations with a hand-wheel become points may require both points to move in the same or in opposite directions in each of the three dimensions of movement. Thus in the fore-aft dimension, the two control points may be linked so that when one point moves forward, the other does also, but linkage could be provided so that when one point moves forward, the other moves backward. Similarly for right-left or up-down motion the two points may move in the same or in opposite directions.

Thus although only three dimensions of movement are possible, several arrangements are available by which these three dimensions may be employed in a two-handed control. For only one dimension did a linkage providing for opposite movements of the two control points seem more rational than one requiring both points to move in the same direction. Considerations of symmetry suggest that for the up-down dimension, control might be better if one point were to move up as the other moved down. We have therefore considered in the present study a set of controls consisting fundamentally of a pair of handlebar grips which could be moved in the following dimensions: (1) in the direction of the forward axis of the airplane (push-pull);

(**) more accurate as the work involved is increased. This suggests the possibility of the operation of similar factors in aircraft control although one might expect in this case that efficiency would not increase indefinitely with increased work required.

*** We may take advantage of the bilateral symmetry of the human body by providing a second symmetrically placed point for manipulation by the other hand when this is possible, but the necessity that manipulation by a single hand shall control the plane demands that we approach the problem as indicated above.

(2) in the "horizontal" direction at right angles to this axis (right-left turn); (3) in the "vertical" direction at right angles to the other two (called by us right-left twist). In the case of this last dimension the grips moved in opposite directions when force was applied, thus duplicating the movements of a wheel on an axis parallel to that of the plane. It should be noted that in order to use such a device for aircraft control the arc through which the wheel shall turn must be small in comparison with the radius of the wheel. Otherwise this movement must have an appreciable lateral component, which is not permissible according to our previous reasoning.

The above analysis leads to the same conclusion reached by a somewhat different route by Henschke and Mauch (2), namely, that only a small number of the possible types of three-dimensional hand controls are feasible.

The Problem

Among the problems of control design which may be attacked by grounded research are the following related problems: (1) What forces must the control mechanism of the prone-flown plane withstand, and (2) What forces may the human organism in the prone position be expected to be able to apply to the control devices? The answers to both these questions demand the same fundamental data -- data concerning the maximum forces which may be applied to a control device by prone subjects. We have set as our problem the collection of these data. It appeared to the writers that design engineers might also find useful information concerning the forces which trained pilots felt they could reasonably be expected to apply to the controls, and place was made in the design of our attack for the collection of these data.

In collecting these fundamental data it is necessary to keep in mind several sub-problems. The fact that planes must be flown by many men makes it important to know something about the extent to which individuals differ with respect to the maximum forces which may be applied in each of the various dimensions of movement by the prone subject. Inasmuch as various plane designs may permit or require greater or less headroom and greater or less freedom of fore- and aft placement of the pilot, it is important to inquire as to the extent to which the subject's position relative to the controls affects the magnitude of the forces which he can apply. Questions as to over-all effectiveness of planes flown from the prone position demand information as to the relative advantage or disadvantage of the prone subject over the seated subject with respect to the maximum forces which may be applied to the controls. We have therefore obtained information concerning the effect of such variation of position of pilot relative to controls and have compared performance in the conventional seated position with performance in the prone position.

The forces which could be applied to the controls were determined for both prone and seated subjects with the same apparatus. In order to study the extent to which the position of the controls relative to the prone pilot influences the magnitude of the forces which he may apply, determinations were made under several conditions. The distance between the horizontal plane of the control grips (center) and the horizontal plane of the tips of the subject's shoulder was varied (three values), as was the distance between the vertical plane of the handlebar grips and the forward tip of the subject's shoulders (three values).

Apparatus

The apparatus used was developed by a process of trial and error. As finally evolved, it possessed the following characteristics. It was sufficiently sturdy so that repeated application of considerable force did not alter its operational characteristics. It provided for three types of movement, each operating in two directions as follows: push-pull, right-left turn, and right-left twist. It provided for minimal movement of the controls with the application of force, that is, an approach to isometric measurement was realized, wherein the handlebars never moved more than two inches under the greatest force applied and usually moved only a fraction of an inch. To allow extensive movement of the controls would have resulted in an effective change in the subject's position with relation to the position of the two control points. Such movements would have introduced an uncontrolled variable, since the position of the control points would vary with the individual subjects depending upon their strength. The apparatus provided for readily altering the position of the subject in reference to the control points in terms of both the horizontal and vertical planes. It was also easily convertible from prone to seated position use.

In order better to follow the subsequent description, it is suggested that the reader refer to Figs. 1 and 2, which are actual photographs of the apparatus.

Prone Position Bed.--

In the prone position, the subject lay on a padded bed, tilted slightly upward from the horizontal. On the higher end of the bed was placed a chest support which was tilted upwards 20 degrees from the bed, further increasing the angle of the subject's line of vision to the absolute horizontal position. The angular position of the bed and chest support, supplemented by the subject raising his head slightly at the neck, permitted horizontal forward vision without extension adjustment of the eye balls. Thus a position of the subject was achieved which other investigators (3) have suggested should be realized for prone position flying.

It was possible to slide the bed forward or backward, thus altering the horizontal distance of the subject from the control points. The three positions of the subject were as follows: in the near position the distance from the forward point of the shoulders to the vertical plane of the handlebar grips was 9 inches, in the middle position of the bed this distance was 13 inches, and in the far position 17 inches. All measurements are for horizontal distances.

The bed platform was hinged at the rear, so that the bed could be raised or lowered in order to change the effective height of the shoulders of the subject in respect to the two control points. Three positions of elevation were used. In the low position the center of the shoulders of the subject were on a level with the points to which the forces were applied to the handlebar grips,* in the middle position the shoulders were 5 inches above these points, and in the high position 10 inches above them. It will be noted that the method of changing elevation makes changes in the tilt of the subject's position. In the low position, the bed itself is tilted 3 degrees from the horizontal, in the middle position $6\frac{1}{2}$ degrees, and in the high position 10 degrees. In each case the tilt is supplemented by the 20 degree tilt of the chest support and the upward movement

* The "points to which the forces were applied" were taken as the points on the control grips where the centers of the subject's hands were located.

of the subject's head and eyes. It is thought that changes in bed angle necessitated by changes in elevation of the shoulders will not result in significant differences in the implications of the data of the present study insofar as the realization of horizontal vision is concerned. Thus in accomplishing a translation of vision from the vertical to the horizontal, through the several types of change in body position previously described, the maximum difference of 7 degrees between the lowest and highest bed position is only a small fraction of the total required change of 90 degrees.

Seated Position.--

For the study of seated position responses, the bed was placed in the low (3 degree) position as used for the prone position. The chest support was removed, and a wide board fastened perpendicularly to the bed and 16 inches from the forward edge of the bed. The front portion of the bed then served as a seat, with the board serving as a back rest. Measuring from the center of the control grips the height of the controls was $11\frac{1}{4}$ inches above the seat. The distance of the control grips forward of the front edge of the seat was 20-3/4 inches. According to data presented in AAF Technical Report 5501 (4), this arrangement is similar to that found in standard cockpits, except that our controls are about 8 inches lower than ordinary wheel type controls and about 3 inches lower than the average stick type control. The distance of the seat to the floor was approximately 18 inches. The seated subject placed his feet on supports which were located on the floor at points approximately 20 inches forward of the front edge of the seat.

Control Column and Measurement System.--

In front of the subject was a standard bicycle handlebar assembly, with the hand grips 16 inches apart. The center of the handlebar rotation was in line with the handlebar grips, so that the radius of rotation was 8 inches. The tube and bearing of the assembly were mounted on an upright post forming the vertical part of the control column. The post was pivoted at its base to the forward end of a horizontal member, which extended backward beneath the bed to a point 22 inches from the post. At this point the horizontal member was secured by means of a pivot. The handlebar assembly was adjusted so the hand grips were located between the bed and the post at a point 6 inches behind the post. The effective radius of movement for the right-left turn, the distance between pivot point and hand grips was then 16 inches and not 22 inches. Locking mechanisms were provided so that motion about one or more of the pivots could be prevented. Thus set up, the subject could move the control column forward and backward (push-pull), or laterally (right-left turn), by application of force on the handlebars, or the handlebars themselves could be twisted in a clockwise or counter-clockwise direction (right-left twist).

The forces applied in any one of these directions were transmitted by means of cables led over pulleys to a lever attached to the plunger of a hydraulic cylinder. This cylinder was a standard "master brake cylinder", Chrysler part No. 695696, and intended normally for use in an automobile brake system. The hydraulic pressure developed within this system was used to operate a calibrated pressure gauge. The experimenter read the dial to the nearest mark which at low pressures was to the nearest pound and at the very high pressures to the nearest five pounds.

It will be noted in the above description, and can be seen by reference to Figs. 1 and 2 (Appendix A), that the push-pull movement is not truly horizontal in its full extent, but is in the form of an arc about the pivot at the end of the post. Similarly, the right-left turn movement is not at right angles to the subject's body but forms an arc with a center near the midpoint of the subject's shoulders. From the standpoint of the subject's operation, however, the movements may be considered as rectilinear, since the amount of movement of the controls was small even when considerable force was applied. At the point on the controls where the subject grasped, it may be said that with the strongest responses and with any dimension of movement tested, the displacement of the control grips did not exceed two inches. Keeping the control column stabilized was achieved in part by locking the controls in neutral in two dimensions of movement while measuring in the third dimension.

For each of the three dimensions of movement, two cables were used, one for each direction of motion. Only the appropriate cable was attached over the pulleys during a measurement trial. Figs. 1 and 2 show all cables attached only for purposes of illustration.

Mention should be made here of the limits involved in this study of the influence of the position of the controls on strength of movement. Not only were the controls fixed in a single position, but each application of force in each movement dimension began with the controls in a physically "neutral" position. For the push-pull dimension the movement did not always start from the neutral point since the distance of the subjects shoulders to the control post was one of the variables studied. Changing the distance of the subject from the control post may be considered as displacement of the controls from the neutral position. For the turn and twist movements strength was tested from the neutral position and never from an extreme position of the controls.

Calibration of the Apparatus.--

The calibration of the apparatus was accomplished by the following procedure. The controls were locked in neutral position for two of the dimensions of movement while leaving free the third movement for calibration. The appropriate cable for the movement being studied was attached to the control column and to the pressure gauge in the same manner as when a subject was being tested. A calibration cable was then attached to the control handles and led over pulleys to a weight pan. On the basis of preliminary tests, a range of calibration weights was established for each movement which was expected to cover the range of forces which subjects were expected to apply. These weights were placed in the pan, and the amount of pressure indicated on the dial for each weight was recorded.

No calibration cable was placed precisely in a rectangular position in reference to the neutral position of the controls since there was a slight displacement of controls under extreme forces. Instead the cable was led away from the control column in such a direction as would provide a means for applying to the controls a force which would be similar to that which a subject would apply. Since the displacement was not rectangular, but curvilinear about the appropriate axis of the controls, the calibration cable was placed so as to be tangent to the arc of movement at a point of displacement corresponding to the estimated mean maximum force which subjects would apply. It was thought that through this procedure the forces applied in the form of weights would more nearly represent the kind of forces subjects would apply. It was found that this arrangement spread the slight curvilinear discrepancies over the whole calibration range so that most curves which were plotted from the data could be treated as straight lines.

It was noted that the results obtained in calibration were a function of the manner in which the weights were placed in the pan. If the weight was lowered into the pan so that its force was gradually applied to the controls the dial reading was somewhat less than if the same weight was applied by beginning with a greater force and gradually lessening it until only the desired weight was on the pan as when consecutive readings are taken for decreasing amounts of force by starting with a pan full of weights and removing one or more weights between consecutive readings. Since the behavior of the subject is to increase the application of force until a maximum effort is reached, the method adopted was that of increasing the weights in the pan until the correct amount of force was applied to the controls.

Experimentation showed that the rate at which weights were applied in approaching a given force was not too critical. As long as the force was applied smoothly, a rapid application of force gave a dial reading almost identical with that obtained by a slower rate of application. Subjects were instructed to apply force smoothly and rapidly, and in calibrating the apparatus the application of increasing amounts of force was similarly accomplished.

<u>Translation of Dial Readings into Pounds of Force</u>.--

Calibration measurements were conducted at the beginning and at the end of the experiment, and additional checks also were made during the experiment. Five or more points were used in determining the curve of relation between dial readings and pounds of force. The final curve fo. each movement was based on an average of 12 to 20 readings for each point measured. All movements except that of "push" yielded straight line functions over the required range of forces. For these movements then, the original data in the form of dial readings were analyzed statistically and then the final constants were converted into pounds of force by multiplying by the calibration constant. Dial readings obtained in the "push" dimension could not be similarly treated because of a curvilinear relation between the two forms of measures. For this movement each subject's performance score was translated from dial reading into pounds of force before statistical analysis was begun.

Experimental Conditions

There was a total of seven experimental sessions for each subject, each session lasting about 50 minutes. Not more than three or less than two sessions were given in any week. The first experimental day for each subject was devoted to preliminary instruction, and to obtaining, for purposes of reliability estimation, maximum and "reasonable" strength efforts which would later be duplicated in the main part of the experiment. In the following six experimental sessions maximum applications of force were obtained for the several different types of movements.

On the first day each subject was oriented with respect to the general purpose of the experiment. He was then placed in position in the apparatus. A standard position of the hands on the control grips was used. If in the prone position the shoulder straps were adjusted to the size of the subject (See Figs. 1 and 2, Appendix A). The subject was instructed to apply force to the controls steadily and rapidly, reaching a maximum effort in from one to two seconds. This was demonstrated to him by the experimenter who placed his hands over the subject's hands on the grips while manipulating the controls. No attempt was made to control the manner in which the subject applied force. Thus one subject might push with his elbows held laterally, while another might make the same effort with his elbows in a downward position. The maximum strength trials were then begun. Four movements - push, left turn, pull, and right twist - were given in that order, the trials being spaced five minutes apart. Performances were recorded for both prone and seated positions. For the prone position the bed was at middle height and middle distance from the controls. For the seated trials the single position of the subject described previously was used throughout the experiment. Half of the subjects did the movements in the prone position first; the other half did them in the seated position first.

The subject was then given further trials, the instruction now being to exert a "reasonable" rather than a maximum force on the controls. The following standard instructions were used:

"Now we want to find out something about the amount of pressure you can exert without straining. You know now what the control system is like. There are six movements: push, pull, right turn, left turn, right twist, and left twist. We are going to ask you to do each of these, one at a time. <u>You are to exert as much pressure as you can and still keep enough reserve so that you feel you could retain control over the other movements, and be prepared to make emergency adjustments, as would be necessary in the flying situation</u>".

The underlined portion of the instructions was repeated, but the instructions were not otherwise expanded, explained, or interpreted for the subject. Performances were recorded in both seated and prone positions for each of the six types of movements. The time between trials was the amount needed by the experimenter to change cables, and approximated one minute in length. Again half of the subjects performed movements in the prone position first, and half in the seated position first.

In the following six days maximum strength in the prone position was investigated for the six movements in nine different bed positions. Each subject was required to make each type of movement once in each position, making a total of 54 strength trials. For the seated position, only six trials, one for each movement, were necessary, since a single position of the subject was used.

The possibility of arranging the movements in random fashion for each subject was considered and discarded. It was decided that the effect on a given movement of the performance of the preceding movement could be more adequately controlled by purposely selecting a given order in a manner that would be least likely to produce a detrimental effect of one movement on a succeeding one. For the main experiment, and for the trials in the "reasonable" strength condition, the order of movements was as follows: left twist, right turn, push, left turn, right twist and pull. This order was used for all bed positions. Different subjects entered the order at different points, that is, Subject number 1 had a protocol calling for left twist as the first movement, the 2nd subject made a right turn as his first movement, the 3rd subject first did a push, and so on. In the main experiment bed positions were randomized, with the qualification that each bed position appear once for each movement.

The six maximum strength trials in the seated position were given in one sitting in the main experiment, and again, the order from first to last movement was rotated as described above. Six "reasonable" strength trials were also given in the main experiment. They were presented in a manner similar to that for the seated position.

Subjects

Sixty-five students at the University of California were used as subjects. All but two were airplane pilots. Of the pilots, most had been or were pilots in the military services. All volunteered for the experiment. Because the experimental sessions involved considerable time the subjects were paid at a nominal rate for their services. Information on age, handedness, and pilot experience was collected. Height, weight, and arm length were measured. A direct measure of arm length was recorded. It was obtained as follows. The subject in the seated position was given a cylinder $1\frac{1}{2}$ inches in diameter to grasp, and then instructed to extended his arm fully vertically without stretching it. A measuring rule was placed so that it rested on the outer end of the clavicle and the distance to the center of the cylinder held in the hand was measured. The cylinder was held so that it was perpendicular to the forearm. The value recorded was an average of the distance thus found for right and left arms. Since each subject was placed in the prone position bed with his shoulders in a standard position, it is apparent that arm length is related to the arm angles measured when the subject was grasping the controls.

These various data descriptive of the subjects are presented in Table 1. The mean age is about one year greater than that of aviation cadets. The height and weight of the group of subjects

Table I.--Personal Data on Experimental Subjects. N = 65

	Mean	Standard deviation
Height (inches)	70.7	2.3
Weight (pounds)	160.	15.
Age (years)	24.4	2.3
*Arm length (inches)	24.8	1.2

*Length of arm from top of clavicle to center of grip with arm extended upwards. (see description of method in text)

Pilot experience	N
Non-pilots	2
1-49 hours	7
50-99 hours	3
100-499 hours	10
500-999 hours	17
1000-1499 hours	15
1500-1999 hours	6
2000-5000 hours	5

Preferred hand

	Right	Left	Ambidextrous
N	58	6	1

is above that for cadets. In mean height the group falls at the 75th percentile for cadets, and in mean weight they fall at the 65th percentile, according to the standards published in AAF Technical Report 5501 (4). In terms of pilot experience, the group is very heterogeneous, flying time varying from zero hours to as many as 4000 hours. All but 12 had 100 or more hours of flying time.

It is apparent that the size of the subjects will be associated to some degree with the values of maximum force applied to the controls. Results obtained in this study, therefore, are not directly comparable with what might be expected from a group of individuals similar in stature to aviation cadets. It would be expected that the mean effort of the individuals studied herein would be somewhat greater. Further discussion of this problem will appear later.

Results

The Data.

The data of the study have been summarized in terms of the means and standard deviations for all movements and all bed positions. This summary is presented in Table 2. Such a summary, however, is inadequate for some purposes, and in order to facilitate comparisons which the reader may desire to make, the histograms and frequency distributions of all fifty four sets of data are presented in Appendix A.

Individual Differences.

There is, of course, no need to inquire whether or not individuals differ with respect to their ability to perform in the present situation. The evidence on such matters has long been overwhelming. It is of importance, however, to establish the fact that our measurements of the maximum forces which may be applied by the various individuals is sufficiently satisfactory to permit us to draw conclusions concerning the relative advantage of one or another of the various dimensions of movement, to estimate the maximum forces which human subjects might apply to the controls, and support other significant generalization concerning prone position control movements.

We have estimated the reliability of our measures by securing duplicate measures on each subject for four of the six movements in the "middle-middle" bed position. We have not replicated measurements in all bed positions, since it appeared to us that although the errors of measurement in the other bed positions may not have precisely the same variance as those in the "middle-middle" position, these variances would not vary among themselves as much as might those of the several movements.

Inasmuch as practical considerations prohibited replicated measurements in all movements and all bed positions, we selected one of each of the two bilaterally symmetrical movements (turn and twist) together with push and pull for replication. Thus for each subject we have two measures of the maximum force he could exert on the controls in the "middle-middle" bed position for right twist, left turn, push and pull. Since each subject was given one test on each of these movements on the first day and since all other tests were given in various orders to the several subjects, the retest was given from two days to two weeks after the original test, with an average of about one week elapsing between original and retest. From these data reliability coefficients have been computed. These coefficients, together with the means and standard deviations of the forces exerted on both first and second trials for both prone and seated position are presented in Table 3.

It must be noted that the unreliability of our measures is contributed to by two broad classes of factors -- those implicit in the apparatus and those implicit in the individual himself (quotidian variability, etc.).

Table 2 summarizes all our findings. Under the assumption that errors of measurement are uncorrelated among themselves and uncorrelated with true scores, the reliability coefficient may be interpreted as the proportion of observed variance which may be attributed to stable differences between the individual subjects involved, and the reader may, if he wishes, estimate "corrected" variances from the standard deviations and reliability

Mean Values

Movement	Low Bed Position Front	Low Bed Position Middle	Low Bed Position Rear	Middle Bed Position Front	Middle Bed Position Middle	Middle Bed Position Rear	High Bed Position Front	High Bed Position Middle	High Bed Position Rear	Prone Means	Seated
Push	114	127	199	132	148	231	134	191	194	163	242
Pull	262	256	257	259	262	257	237	240	237	252	199
R. Turn	112	106	92	123	107	95	113	103	85	104	88
L. Turn	107	103	89	115	102	90	111	94	80	99	86
R. Twist	139	127	108	126	116	101	127	115	96	117	152
L. Twist	138	129	111	128	117	100	131	116	94	118	151
Means	145.3	141.3	142.7	147.2	142.0	145.7	142.2	143.2	131.0	142.3	153.0

Standard Deviations

Movement	Low Bed Position Front	Low Bed Position Middle	Low Bed Position Rear	Middle Bed Position Front	Middle Bed Position Middle	Middle Bed Position Rear	High Bed Position Front	High Bed Position Middle	High Bed Position Rear	Seated
Push	22.4	31.8	75.4	27.4	40.5	55.3	34.1	42.4	46.1	56.7
Pull	58.2	47.7	43.8	50.0	44.2	41.8	40.1	41.7	38.7	30.8
R. Turn	28.3	25.0	23.0	27.9	24.3	22.4	29.2	22.7	22.2	23.7
L. Turn	33.3	27.9	22.1	29.7	24.0	21.1	25.0	21.2	19.2	19.0
R. Twist	26.1	23.8	19.7	24.6	21.1	20.2	20.7	22.4	22.0	31.5
L. Twist	29.6	23.7	20.9	23.2	22.5	21.8	24.0	23.3	21.5	33.3

Table 2.--Maximum Strength: Means and Standard Deviations for Six Movements in Nine Bed Positions for Seated and Prone Positions. N = 65

Table 3.--Maximum Strength; Means, Standard Deviations, and Reliability Coefficients for Four Movements (Right Twist, Left Turn, Push, and Pull) in the Prone and Seated Position. Measurements in the Prone Position Taken for Middle Elevation and Middle Distance of Bed with Reference to Controls. All Measurements in Pounds.
N = 65

Prone Position

	Right Twist	Left Turn	Push	Pull
Mean 1st trial	112.	96.	152.	250.
Mean 2nd trial	116.	102.	148.	262.
Standard deviation 1st trial	24.	27.	45.	48.
Standard deviation 2nd trial	21.	24.	41.	44.
Correlation between 1st and 2nd trial	.73	.75	.55	.68

Seated Position

	Right Twist	Left Turn	Push	Pull
Mean 1st trial	138.	83.	227.	183.
Mean 2nd trial	152.	86.	242.	199.
Standard deviation 1st trial	30.	24.	60.	42.
Standard deviation 2nd trial	32.	19.	57.	31.
Correlation between 1st and 2nd trial (uncorrected)	.69	.56	.61	.45

Prone Position	N	Right Twist	Left Twist	Right Turn	Left Turn	Push	Pull
Mean 1st trial	58	74.	69.	63.	60.	98.	162.
Mean 2nd trial	58	76.	74.	66.	63.	99.	171.
Standard deviation 1st trial	58	29.	27.	23.	23.	34.	65.
Standard deviation 2nd trial	58	27.	28.	23.	21.	33.	56.
Correlation between 1st and 2nd trial (uncorrected)	58	.81	.80	.70	.73	.80	.82
Ratio of means of two trials to mean maximum forces (from Table 2)		.64	.60	.62	.62	.60	.66
Seated Position							
Mean 1st trial	59	86.	85.	54.	54.	129.	140.
Mean 2nd trial	59	86.	88.	54.	55.	131.	144.
Standard deviation 1st trial	59	30.	31.	19.	18.	50.	47.
Standard deviation 2nd trial	59	33.	33.	18.	20.	55.	44.
Correlation between 1st and 2nd trial (uncorrected)	59	.85	.78	.80	.83	.83	.84
Ratio of means of two trials to mean maximum forces applied in seated position		.39	.57	.61	.63	.54	.71

Table 4.--"Reasonable" Strength: Means, Standard Deviations, and Reliability Coefficients for Six Movements in the Prone and Seated Position. Measurements in the Prone Position taken for Middle Elevation and Middle Distance of Bed with Reference to Controls. All Measurements in Pounds.

coefficients presented in Table 2 and Table 4. This corrected variance is the product of the observed variance and the appropriate reliability coefficient. For the purpose of estimating these "corrected" variances it must be assumed that for other bed positions than those for which reliability data were obtained, the reliabilities would have been substantially the same as those for which we have the data.

These "corrected" variances reflect the variability among individuals which remains after removing the variation due to errors of apparatus and to erratic performances of individual subjects. Since these latter factors reduce the reliability coefficient but are nevertheless important contributors to the variability in which the design engineer must be interested, the variance properly reflecting this interest is intermediate between the raw variance and the "corrected" variance--probably nearer the former than the latter, as will be seen later.

It will be noted from Table 3 that in general the reliabilities for the prone position are higher than the corresponding reliabilities for the seated position, although in the case of "push", seated is the more reliable. Of interest also is the consistent improvement reflected in this table between first and second trial, as well as the decrease in both absolute and relative variability of the group in the case of each of the six directions of movement.

In Table 4 is presented the same information concerning the forces which pilots feel to be the maximum they could reasonably be expected to apply to the controls. This information was obtained in duplicate for each of the six movements investigated. It is of interest to notice that of the four coefficients in this table which correspond to those in Table 3, three & are greater for "reasonable" forces than for "maximum" forces. In general the "reasonable" measurements are considerably more reliable than the "maximum" ones. This finding implies that our individual subjects were more stable from day to day with respect to their concept of the maximum forces which they could apply and still retain control of other movements than with respect to the maximum forces which they could actually apply. This finding is somewhat surprising and suggests considerably more stability to such purely subjective phenomena than we had expected to find. It suggests, further, that a major part of the unreliability of our "maximum" forces is due to intra-individual differences rather than to pure apparatus unreliability, hence our earlier emphasis on the raw variances rather than the "corrected" ones. Notice, for example, that in the case of the "push" movement for the prone position, 55% of the total variance of maximum forces is accountable for in terms of stable individual differences (i.e., the reliability coefficient is 0.55), while 80% of the variance of the maximum "reasonable" forces is to be thus explained.

Also of interest in connection with this aspect of the study is the fact that although the absolute variability of "maximum" and "reasonable" forces is essentially of the same order of magnitude, the mean "reasonable" forces are smaller than the mean "maximum" forces, and hence the relative variabilities of the "reasonable" forces are greater.

Comparison of Prone and Seated Position.

Table 5 presents the comparison of performance on the six dimensions of movement in the prone and seated positions. The means presented for the prone position are the means of the nine means (from the nine bed positions) for each of the movements.[1] The mean presented for the seated position is the single mean obtained for the 65 subjects in the only seated position investigated -- a position approximating that of the conventional cockpit.

Also presented in this table is the standard deviation of the nine means entering into each of the prone position means presented in the table. A small value of this standard deviation implies that performance for the movement in question is not sensitive to variations in the position of the pilot relative to the controls. A large value, on the other hand, implies greater sensitivity to such variations.

Comparison of the prone and seated averages reveals that the seated position is definitely superior in the case of three movements, while for the remaining three movements the prone position is superior. It is therefore of importance to consider the nature of the movements and the possible control surfaces to be manipulated by the movements in which each of these two positions is superior. The seated position appears to be superior in right twist, left twist, and in push. The most rational linkage of these movements to the plane controls would appear to be the one in which the right-left twist would be linked to ailerons and push-pull would be linked to the elevators. The prone position appears to be superior in the case of left turn, right turn, and pull. These dimensions of movement would probably be linked to rudder and elevators, respectively. Reference to Table 2, however, reveals that the disadvantage of the prone position may be minimized by adjusting the location of the pilot relative to the controls, but even then the best averages in the prone position for right-left twist and push are inferior to the corresponding values for the seated position.

Conclusions as to the over-all advantage or disadvantage of the prone position insofar as it depends on maximum forces applicable, then, must depend upon considerations of the relative frequencies (and importance) of occurrence in operational flights of occasions which necessitate application of near-maximal forces to ailerons and to elevators (e.g., in a dive).

Table 5.—Maximum Strength: Prone vs. Seated Performance.
N = 65

Movement	Mean of Nine Prone Means	Seated Mean (one determination)	Standard Deviation of Nine Prone Means
Push	163.	242.	38.6
Pull	252.	199.	10.0
Right Turn	104.	88.	11.1
Left Turn	99.	86.	10.8
Right Twist	117.	152.	13.1
Left Twist	118.	151.	12.9

Position of Prone Pilot Relative to Controls.

The fundamental data of Table 2 have been rearranged in Tables 6, 7 and 8 for convenience in considering the influence on performance of the pilot's position relative to the controls. While these tables themselves seem to form a satisfactory basis for interpretation, we have submitted the 54 prone means of Table 2 to analysis of variance, and the summary of this analysis is presented in Table 9. "F" values have not been computed, since the purpose of this analysis was simply to obtain an idea concerning the interactions of movements by the two species of bed position.

This analysis indicates that by far the greater part of the total variance among these fifty four means is to be ascribed to the great differences in the forces which may be applied to the various dimensions of movement. Very little of the total variance can be ascribed primarily to either the horizontal or the vertical position of the bed. An appreciable part of the total variance must be ascribed, however, to the interaction of specific movements and horizontal position. Reference to Table 6 reveals that this is due almost exclusively to the atypical behavior of "push" as the bed is moved from front to rear. Although all other movements suffer somewhat as the bed is moved to the rear, "push" improves and improves very dramatically.

In view of this interaction, it is important to scrutinize the change in performance with change in horizontal bed position for the individual movements. Table 6 shows that for all movements but push, performance scores become lower on the average as the bed is moved from front to rear. Table 7 reveals no such consistency in the case of vertical position, though there is a tendency for the middle position to be superior. As a matter of fact, Table 2 reveals that the middle front position yields the highest mean of the six movement means.

Discussion

Forces Which the Controls Must Withstand.

The results summarized in the preceding section offer a means of estimating the maximum forces which must be sustained by the controls. This estimate, however, must be based on several assumptions.

The Sample. It would appear from the descriptions of height and weight of the men included in our sample that we do not have a random sample of pilot cadets. We have carefully considered our method of recruiting subjects for this experiment and can find no reason to believe that our selective procedures would yield an unrepresentative sample of service pilots attending the University of California. We must thus conclude either that experienced pilots differ from cadets

Table 6.—Maximum Strength: Means for the Three Horizontal Bed Positions and for Seated. Means in Pounds.
N = 65

Movement	Horizontal Position Front	Middle	Rear	Mean Prone	Seated
Push	126.7	155.3	208.0	163.3	242.
Pull	252.7	252.7	250.3	251.9	199.
R. Turn	116.0	105.3	90.7	104.0	88.
L. Turn	111.0	99.7	86.3	99.0	86.
R. Twist	130.7	119.3	101.7	117.2	152.
L. Twist	132.3	120.7	101.7	118.2	151.
Means	144.9	142.2	139.8	142.3	153.

Table 7.—Maximum Strength: Means for the Three Vertical Bed Positions and for Seated. Means in Pounds. N = 65

Movement	Vertical Position			Mean	Seated
	Low	Middle	High		
Push	146.7	170.3	173.0	163.3	242.
Pull	258.3	259.3	238.0	251.9	199.
R. Turn	103.3	108.3	100.3	104.0	88.
L. Turn	99.7	102.3	95.0	99.0	86.
R. Twist	124.7	114.3	112.7	117.2	152.
L. Twist	126.0	115.0	113.7	118.2	151.
Means	143.1	144.9	138.8	142.3	153.

Table 8.—Maximum Strength: Means for the Nine Bed Positions in Pounds and the Mean for the Seated Position.
N = 65

Vertical Position	Horizontal Position		
	Front	Middle	Rear
Low	145.3	141.3	142.3
Middle	147.2	142.0	145.7
High	142.2	143.2	131.0
Means	144.9	142.2	139.7
Total Prone Mean			142.3
Seated Mean			153.0

Table 9.—Maximum Strength: Analysis of Variance Among the 54 Means. (6 movements, 3 horizontal and 3 vertical bed positions)

Source of variation	df.	SS.	MS.
Movements	5	153,002.83	30,600.56
Horizontal Bed Positions	2	235.44	117.72
Vertical Bed Positions	2	361.00	180.50
Movement X Horizontal	10	14,610.56	1,461.05
Movement X Vertical	10	2,598.33	259.83
Horizontal X Vertical	4	446.57	111.64
Movement X Horizontal X Vertical	20	1,518.10	75.90
Total	53	172,772.83	

df. = degrees of freedom
SS. = Sums of squares
MS. = Mean square

with respect to these characteristics, or that those service pilots electing to complete their college training at the University of California differ from those pilots not electing to continue their college education or electing to attend some other university. We are inclined to suspect that -- although seasoned pilots probably do differ from cadets in these respects -- the pilots electing to continue their college work at the University of California are taller and heavier (and therefore stronger) than their colleagues elsewhere. However, if we assume that our present sample of 65 cases is an unbiased sample of trained pilots, the error involved from this assumption for the purpose of estimating the maximum forces which the controls must withstand will be a conservative one.

Form of Distribution. On the assumption that the sample studied is not a biased sample of service pilots, it is then necessary to make some assumptions concerning the form of the distribution of the population of which we have a random sample. From a sample of only sixty-five cases, inferences concerning population form (skewness, kurtosis, etc.) are undependable owing to the large standard errors of the moment coefficients. In the absence of overwhelming evidence to the contrary, therefore, the simplest assumptions may serve as an approach to the general problem of the maximum forces which the controls must withstand. We propose, then, to assume the distribution to be "normal" and to attempt on this basis to estimate the maximum values which must be provided for.

Assuming strict normality makes impossible an answer as to exact values for these maximums, since the normal distribution is asymptotic to the base line. We may, however, estimate some high percentiles and accept the risk specified by those percentiles. We have made these estimates in the following manner: We have assumed all distributions to be "normal". We have estimated the standard deviation of the population by the method of maximum likelihood from the variance of our sample in the bed-position yielding the greatest variance. We have assumed for the mean of the population the observed mean in the most favorable bed-position. Inasmuch as the six movements are in reality three pairs of reciprocal movements, we have not made independent estimates of these percentiles for each of the two members of a pair, but have assumed for our population mean the value equal to the better of the two best means and have estimated the population standard deviation on the basis of the larger of the two largest standard deviations. On these assumptions we have computed the 99th, the 99.5th, the 99.9th, and the 99.99th percentiles of these distributions. The results of these computations are presented in Table 10.

The problem of the maximum forces which must be provided for may be approached from a slightly different point of view. We may ask, "In samples of N individuals, on the average how much force will be exerted by the most powerful individual?" This general problem has been discussed in the statistical literature and its solution provided for the case of random samples drawn from a normal population (5). The probability integral of the distribution of the largest individual in samples of a given size from a normal population also permits us to discover in what proportion of samples the extreme individual will apply more than any specified force to each of the various dimensions. We have presented in Table 10 also the average for samples of 500 men of the maximum forces to be expected of the most powerful men in those samples. Presented also is the 80th percentile of maximums of most powerful men in samples of 500 cases each -- i.e., the strongest man in 80 out of every 100 random samples of 500 cases each will apply forces not greater than the values presented in the last column of Table 10.

<u>The Maximum Forces Which May Be Applied by Weaker Pilots.</u>

From the point of view of both design engineers and those responsible for the training of pilots, the forces applied by the weaker pilots also form a very important problem. When this problem is approached, however, the limitations of the assumption of normality are even more obvious. We have, however, estimated the 1st, 0.5th, and 0.1th percentiles of the populations specified in Table 10. They are presented in Table 11. It should be kept in mind that for the most advantageous bed-positions, none of our subjects exerted such small forces as the first percentiles recorded in Table 11, although several exerted forces equal to or greater than the 99th percentiles of

Dimension	Estimated Population Mean	Estimated Population St. Deviation	P99	P99.5	P99.9	P99.99	*	**
Push-Pull	262	76.2	439	458	498	545	494	516
Turn	123	33.6	201	210	227	248	225	235
Twist	139	29.9	209	216	232	250	230	239

* On the average, the strongest man in samples of 500 men will apply a force not greater than this.

** The strongest man in 80 out of 100 samples of 500 men each will exert a force not greater than this.

Table 10.--Maximum Forces (in pounds) Applied to the Various Dimensions of the Three-Dimensional Control Device by Stronger Pilots.

Dimension	Estimated Population Mean	Estimated Population St. Deviation	P 1	P 0.5	P 0.1
Push-Pull	262	76.2	85	66	26
Turn	123	33.6	45	37	20
Twist	139	29.9	69	62	47

Table 11.--Maximum Forces (in pounds) Applied to the Various Dimensions of the Three-Dimensional Control Device by Weaker Pilots.

Table 10. The fact that the maximum forces which the weakest pilots can apply may be very small, may make necessary a more rigorous selection of pilots of prone-flown planes, though the absence of comparable data for stick-and-rudder forces makes it impossible for us to make recommendations on this point.

<u>Optimal Placement of the Pilot Relative to the Controls</u>.

In order to have visual evidence concerning this matter Table 12 has been prepared. Unfortunately, as has been noted in the presentation of our results, neither prone or seated position is consistently advantageous.

With respect to the optimal prone position, the table suggests either position LF or MF -- either the low front position or the middle front position -- as optimal. But as we have observed elsewhere, the optimal position must depend upon considerations of the relative frequency with which force must be applied in each of the several dimensions, and in ignorance of these facts, we are unable to make recommendations concerning this matter. The facts presented in Table 12, taken in conjunction with these other considerations should provide the answer to the problem at least insofar as the answer is dictated by considerations of the maximum forces which the pilot must apply.

Movement	Bed Position									Mean of all prone positions in pounds	Seated in relation to prone, in percentages
	LF	LM	LR	MF	MM	MR	HF	HM	HR		
Push	70	78	122	81	91	142	82	117	119	163	148
Pull	104	102	102	103	104	102	94	95	94	252	79
Right Turn	108	102	88	118	103	91	109	99	82	104	85
Left Turn	108	104	90	116	103	91	112	95	81	99	87
Right Twist	119	109	92	108	99	86	109	98	82	117	130
Left Twist	117	109	94	108	99	85	111	98	80	118	128

Table 12.--Maximum Strength: Mean Forces Applied in Each Movement Expressed as a Percentage of the Over-all Mean (all bed positions) for That Movement, Together With Over-all Mean Forces (in pounds) for Each Movement. N = 65

Summary and Conclusions

Sixty-three men with service pilot experience and two non-pilots were tested on a three-dimensional hand-control device suitable for use as a control for a prone-flown plane. The maximum forces which they could apply to the controls in each of six directions in each of nine bed-positions and in the seated position were measured. Evidence was also obtained concerning the forces which it seemed to these pilots reasonable to expect them to apply to the controls in both prone and seated positions.

As was expected, large individual differences were observed. In certain of the directions in which the subjects were required to apply force the prone position was, on the average, superior to the seated position. In certain other directions the seated position was superior. The relative superiority of the prone position in those directions in which it was superior was as great as the relative superiority of the seated position for its most advantageous directions.

In the case of the prone position, the position of the bed, in terms of both its vertical and its horizontal placement, was found to influence the magnitude of the forces which may be applied, but these influences are small.

Since the relative advantage of the prone or seated position with such controls as have been investigated by us depends not alone on maximum forces applicable, but upon the control surfaces to be operated by these various directions of control movement, and upon the relative frequency in operational flight with which maximal application of force is required in each of the various dimensions, we have not attempted an evaluation of the relative advantage or disadvantage of the prone position in conjunction with controls of the type investigated. We find no very convincing evidence, however, that the prone position will be at a disadvantage over the seated position with respect to forces applicable to the controls; indeed, for some movements which might be most important in combat flight the prone position has a definite advantage.

For the same reasons we are unable to discuss the relative over-all advantage or disadvantage of the prone position, but we have presented data necessary to the determination of that optimal position.

We find that if such controls as those investigated are to be employed in prone flown aircraft, provision must be made to permit them to withstand forces applied by pilots of about 500 pounds in the push-pull dimension and of about 250 pounds in the other dimensions.

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APPENDIX A

(1) Photographs of apparatus used for "Magnitude of Forces Which May Be Applied by the Prone Pilot to Aircraft Control Devices. 1. Three-Dimensional Hand Controls."

(2) Tables of frequency distributions for the movements investigated.

(3) Graphs of the distributions of force applied in each position and for each movement.

Figure 1

APPARATUS FOR FORCES APPLIED TO CONTROLS

Showing the control column, hand grips, cables to hydraulic system, chest support and shoulder straps.

Note: Cables are all shown attached for purposes of illustration only.

U. of Calif., 1949, Contract No. 15093

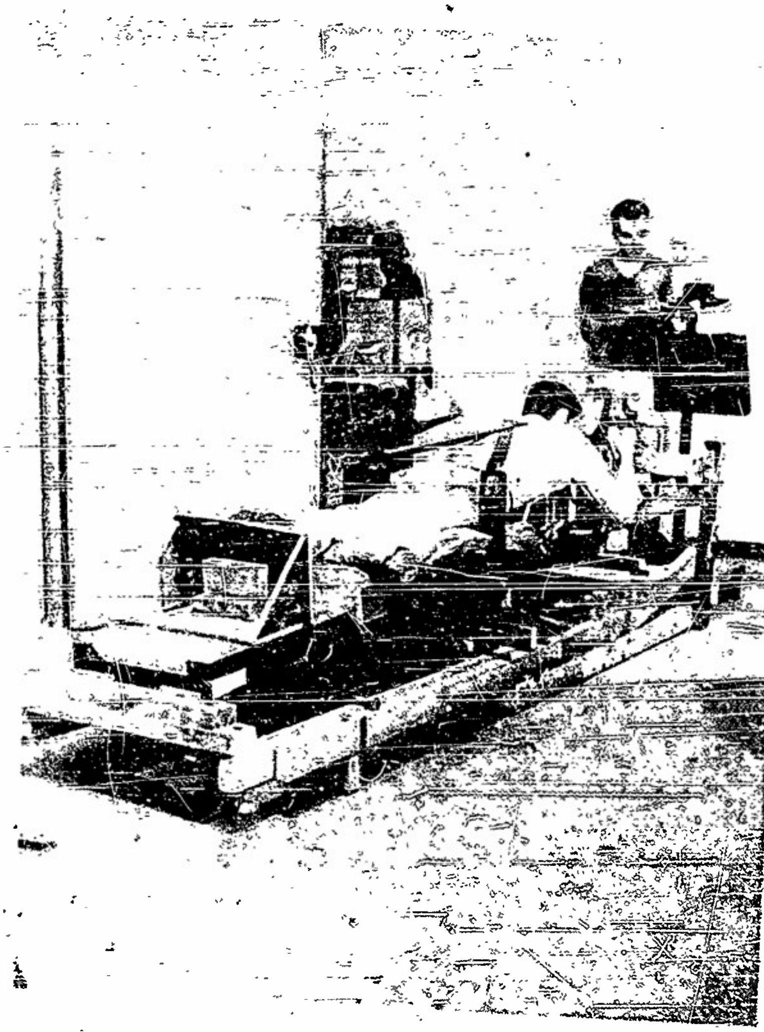

Figure 2

APPARATUS FOR FORCES APPLIED TO CONTROLS

Showing foot support, ankle support, shoulder straps and general subject positioning.

U. of Calif., 1949, Contract No. 15098

Table 13.—Frequency Distributions of Forces Exerted for Maximum Strength, Push, in Each Prone Bed Position and in the Seated Position. N = 65 (except HM, N = 64)

Force in Pounds	LF	LM	LR	MF	MM	MR	HF	HM	HR	SEATED
460-479			1							1
440-459										
420-439										
400-419										
380-399										1
360-379										1
340-359			3			1				1
320-339			2			4				1
300-319			1			2			1	2
280-299			3		1	8	1	1	2	5
260-279			3		2	6		4	2	6
240-259			4			7		6	6	14
220-239			8		1	8		6	6	8
200-219		2	3	2	3	11	1	8	10	10
180-199		5	2	2	3	7	3	10	13	6
160-179	1	2	11	4	8	4	4	12	11	7
140-159	8	9	11	17	14	3	20	11	8	2
120-139	11	18	8	19	21	4	18	5	3	
100-119	31	19	2	14	10		12	1		
80-99	10	8	3	6	2		3		3	
60-79	3	2		1			3			
40-59	1									

Table 14.—Frequency Distributions of Forces Exerted for Maximum Strength, Pull, in Each Prone Bed Position and in the Seated Position. N = 65

Force in Pounds	LF	LM	LR	MF	MM	MR	HF	HM	HR	SEATED
380-399	1	1						1		
360-379	5	1		2	2	1				
340-359		1	2	4	2	2	1		2	
320-339	5	1	3	1	1	1	1	1		
300-319	2	6	4	4	8	4	3	2	2	
280-299	10	13	14	10	8	13	4	4	4	1
260-279	14	4	8	11	10	8	8	11	9	
240-259	11	19	14	15	19	16	14	15	14	5
220-239	2	6	8	3	7	7	14	11	13	13
200-219	3	3	4	9	2	7	8	11	9	9
180-199	5	7	5	3	3	4	7	5	8	20
160-179	4	2	1	1	1	2	3	2	2	11
140-159	3		2	1	2		2	2	2	4
120-139										1
100-119										1
80-99				1						

Table 15.—Frequency Distributions of Forces Exerted for Maximum Strength, Right Turn, in Each Prone Bed Position and in the Seated Position. N = 65

Force in Pounds	LF	LM	LR	MF	MM	MR	HF	HM	HR	SEATED
190-199	1			1						
180-189				1						
170-179	1				1		2			
160-169	2	1		5		1	1	2		
150-159	2	2		6	1	1	6	1		1
140-149	5	5		6	6		2	1	2	1
130-139	6	3	3	7	5	2	9	3	1	1
120-129	7	9	5	8	7	2	5	7	2	5
110-119	11	11	10	7	7	10	12	9	3	6
100-109	5	7	8	7	9	11	8	15	8	3
90-99	8	9	8	11	11	10	4	7	10	11
80-89	10	9	10	5	10	12	6	7	12	6
70-79	6	4	10		3	9	7	9	7	14
60-69		3	7	1	4	3	2	4	14	12
50-59	1	1	2		1	2			3	4
40-49		1	1			1			3	
30-39			1			1				1
20-29							1			

Table 16.—Frequency Distributions of Forces Exerted for Maximum Strength, Left Turn, in Each Prone Bed Position and in the Seated Position. N = 65

Force in Pounds	LF	LM	LR	MF	MM	MR	HF	HM	HR	SEATED
210-219	1			1						
200-209										
190-199							1			
180-189										
170-179	1	1		1			1			
160-169	1	1		2	1					
150-159	2	2	1	2	1		2	1		
140-149	2	2		6	3	1	2	1		
130-139	9	5	1	6	2	2	5	2	2	
120-129	10	6	4	10	11	4	10	3		4
110-119	4	9	5	9	7	5	12	9	2	4
100-109	9	10	9	10	10	8	14	10	5	10
90-99	6	7	10	6	7	12	5	14	8	10
80-89	2	9	15	4	11	10	9	7	14	10
70-79	10	7	8	4	7	14	1	10	19	13
60-69	4	4	6	1	4	4	2	5	6	8
50-59	1		4	3	1	4		3	4	5
40-49	3	2	1			1	1		3	1
30-39			1						2	

Table 17.—Frequency Distributions of Forces Exerted for Maximum Strength, Right Twist, in Each Prone Bed Position and in the Seated Position. N = 65

Forces in Pounds	LF	LM	LR	MF	MM	MR	HF	HM	HR	SEATED
210-219	1									4
200-209	1			1						1
190-199	1	1								3
180-189	1	1					1			6
170-179	3	1		1	1		1	1		7
160-169	4	1	1	2	1		1		1	5
150-159	8	5		3	2		6	2		4
140-149	8	4	1	10	4	1	6	7	2	13
130-139	14	14	7	9	9	2	8	5		8
120-129	9	17	10	18	11	12	21	13	3	3
110-119	7	11	10	8	16	6	9	13	6	5
100-109	1	1	14	3	5	12	4	9	10	3
90-99	6	2	9	5	9	15	4	5	21	2
80-89	1	5	6	4	3	6	4	4	11	.
70-79		2	5		3	7		5	3	1
60-69			2		1	3			3	
50-59								1	4	
40-49				1		1			1	

Table 18.--Frequency Distributions of Forces Exerted for Maximum Strength, Left Twist, in Each Prone Bed Position and in the Seated Position. N = 65

Forces in Pounds	LF	LM	LR	MF	MM	MR	HF	HM	HR	SEATED
220-229	1									2
210-219										
200-209		1								5
190-199	2						1			1
180-189	2						1			4
170-179	5	1		4	1		3			5
160-169	5	2	1		1		2	2		9
150-159	6	7	1	7	2	2	5	2		7
140-149	7	6	1	9	6		13	7	2	11
130-139	11	14	10	13	8	2	9	6	1	2
120-129	7	11	7	9	12	8	10	13	4	7
110-119	8	9	18	8	8	4	8	12	10	6
100-109	3	10	9	7	11	18	5	5	5	2
90-99	6	2	8	3	8	13	5	8	19	2
80-89	1	1	5	4	4	7	3	7	6	2
70-79	1		3	1	4	3		1	8	
60-69			1			4		1	6	
50-59		1	1			4		1	2	
40-49									2	

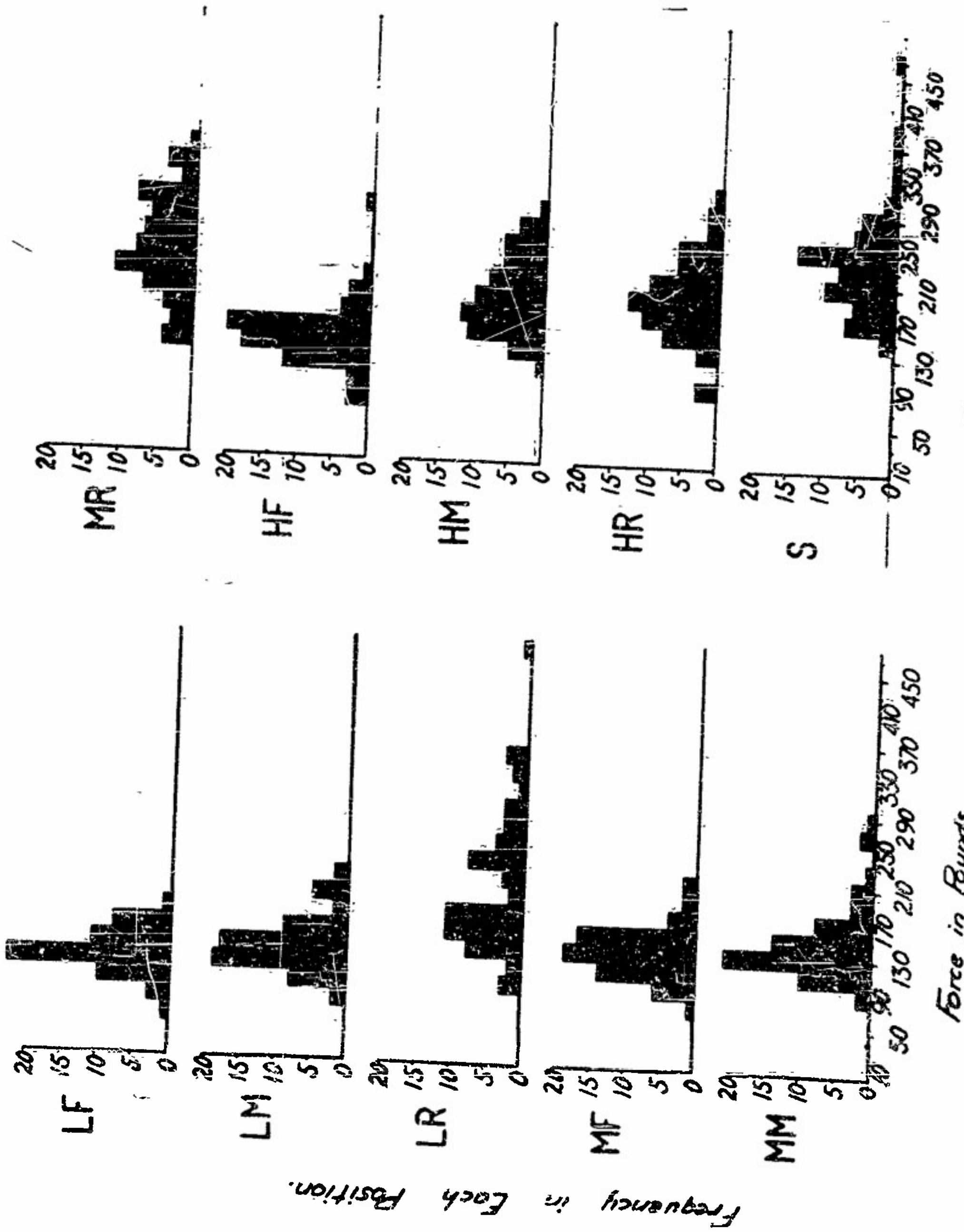

FIGURE 3 - Frequency Distribution of Forces Exerted for Maximum Strength, Push in Each Prone Bed Position and in the Seated Position N=63 except HM=64

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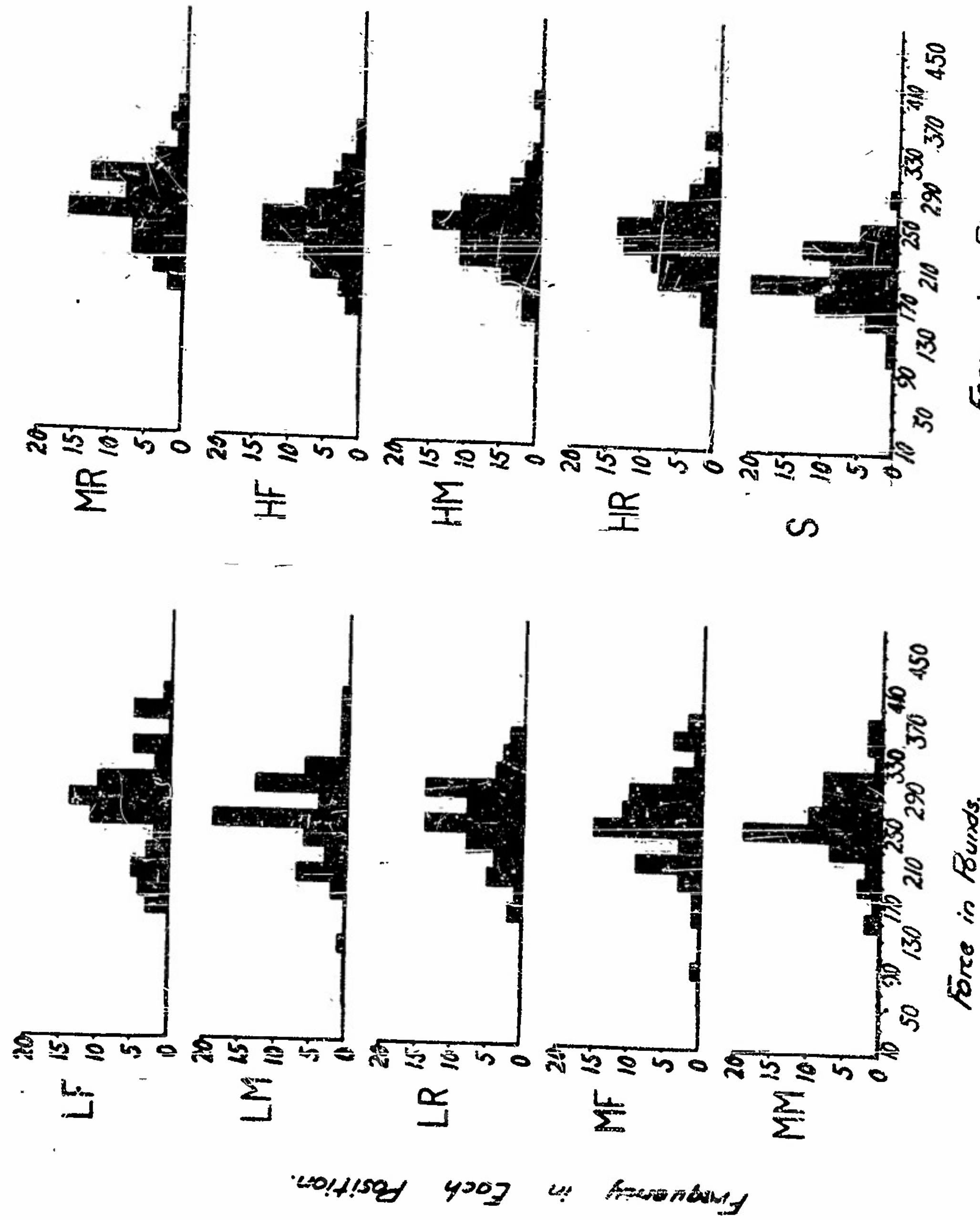

FIGURE 4 - Frequency Distribution of Forces Exerted for Maximum Strength, Pull in Each Prone Bed Position and in the Seated Position - N=65

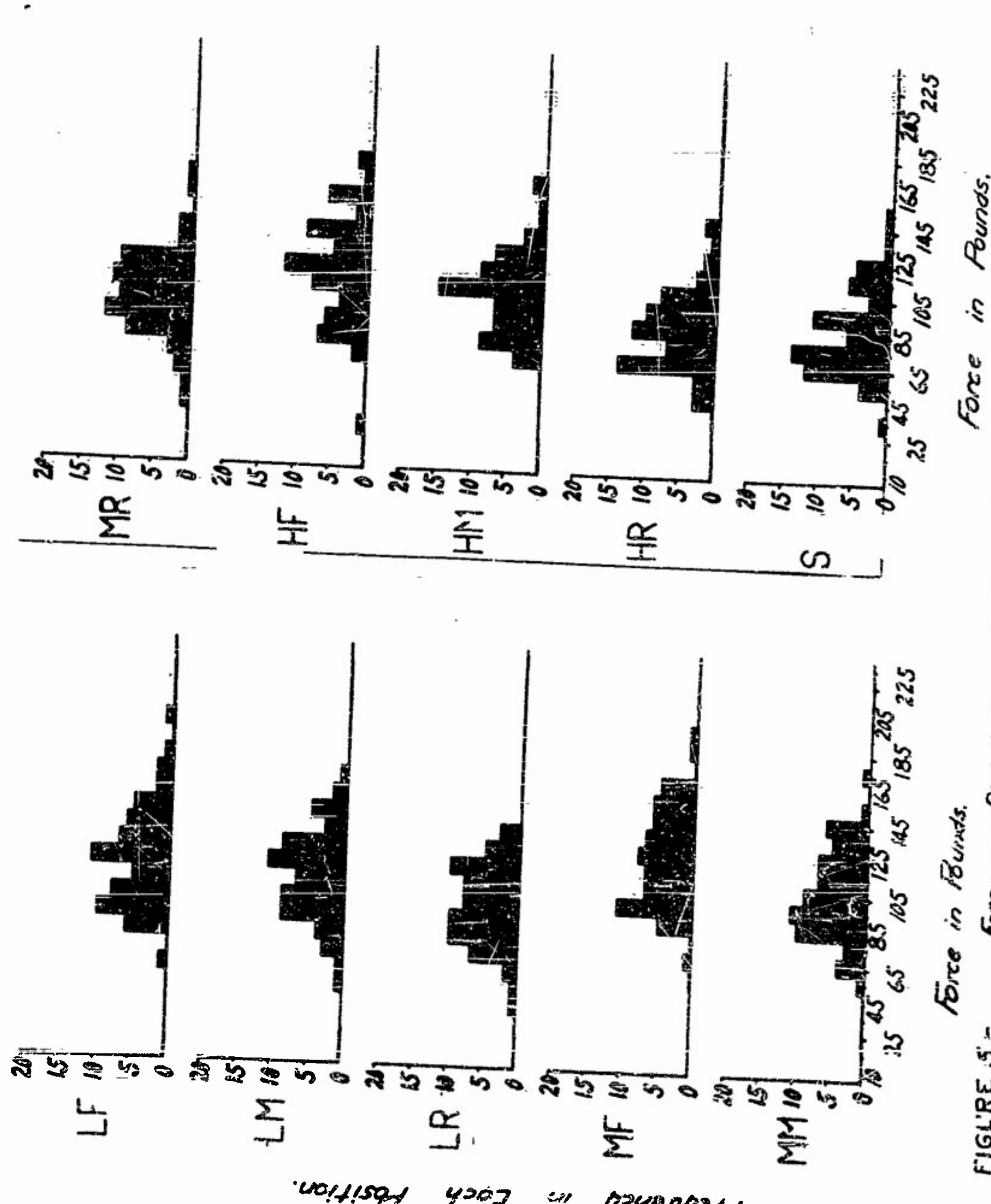

FIGURE 5 - Frequency Distribution of Forces Exerted for Maximum Strength, Right Turn in Each Prone Bed Position and in the Seated Position - N=55

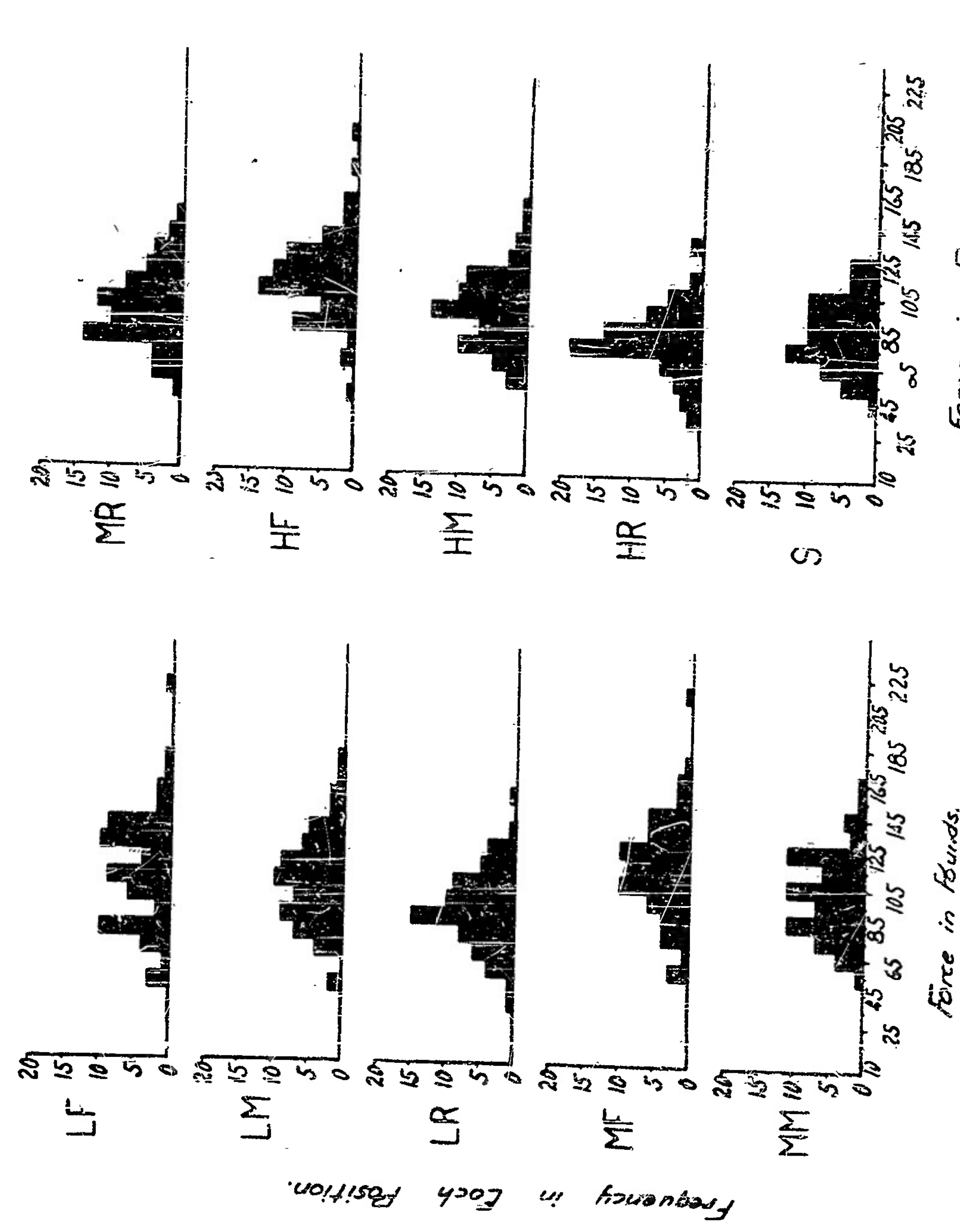

FIGURE 6 - Frequency Distribution of Forces Exerted for Maximum Strength, Left Turn in Each Prone Bed Position and in the Seated Position - N=65

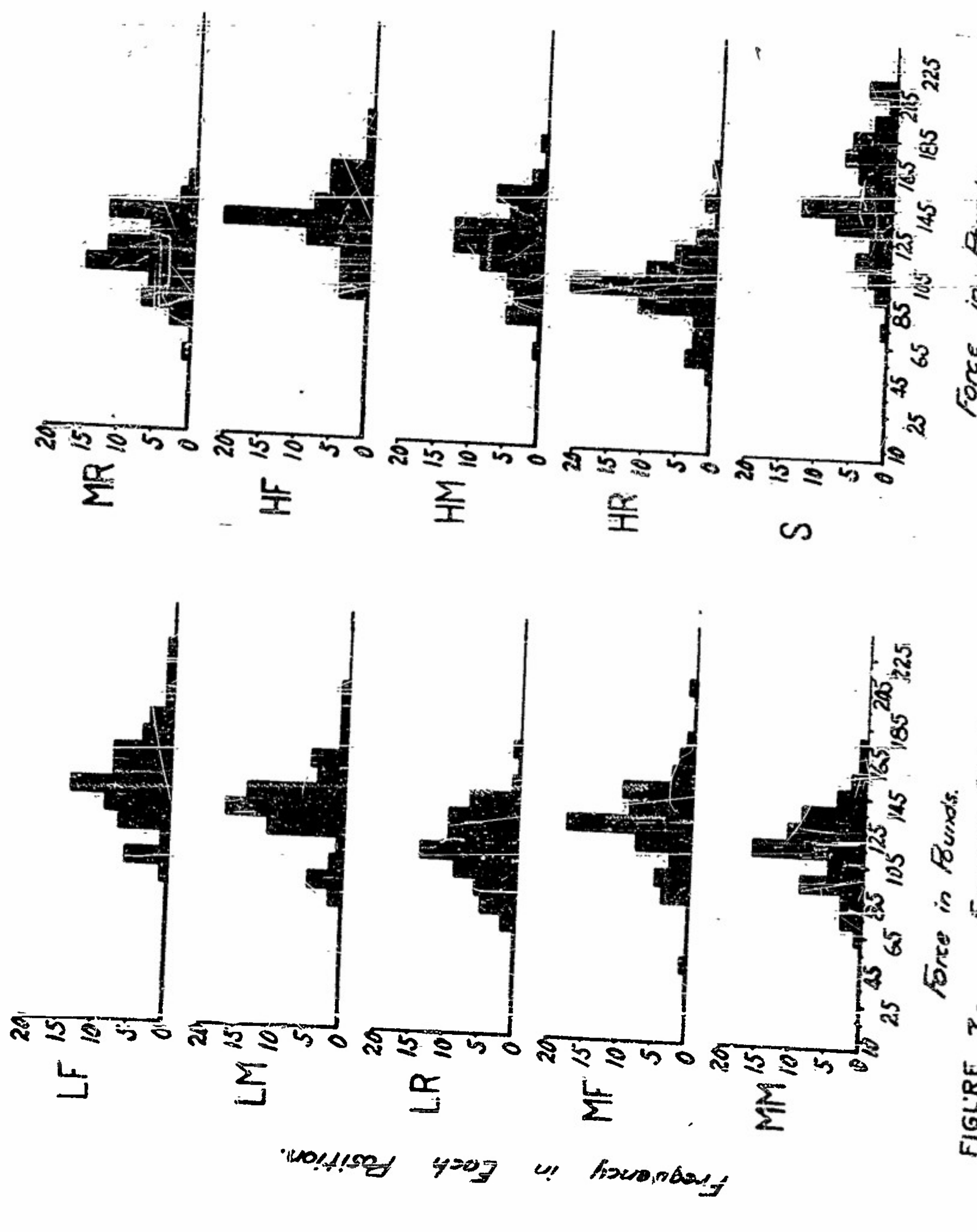

FIGURE 7- Frequency Distribution of Forces Exerted for Maximum Strength, Right Twist in Each Prone Bow Position and in the Seated Position - N=65

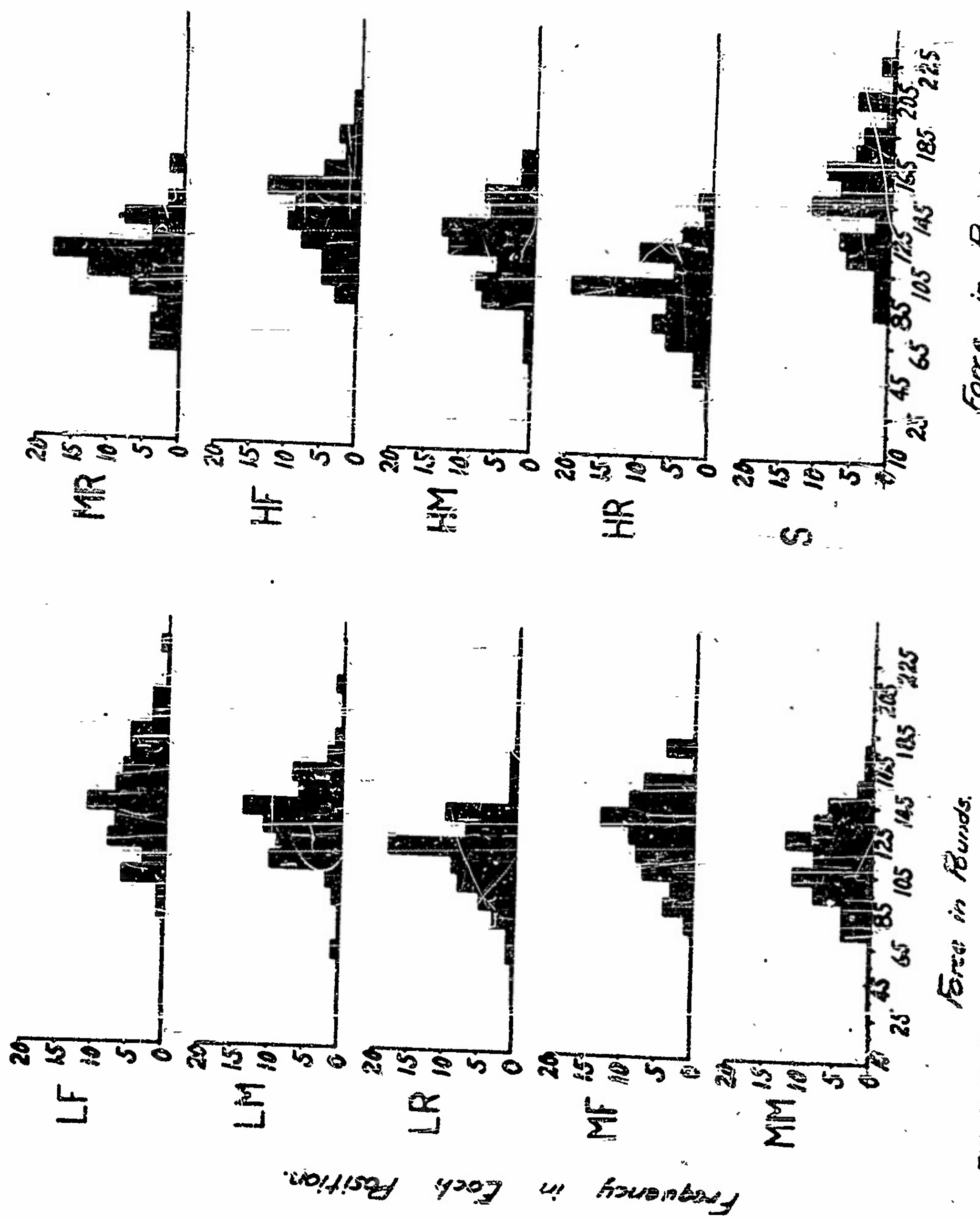

FIGURE 8 - Frequency Distribution of Forces Exerted for Maximum Strength, Left Twist in Each Prone Body Position and in the Sitting Position - N-65

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